Partons meet spectroscopy: Transverse densities from timelike form factors
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- Transverse hadron structure
  - Why partonic description
  - Transverse densities from elastic FFs
  - Connection with GPDs

- Nucleon transverse charge density
  - Dispersion representation of $\rho(b)$
  - Zooming in on exchange mechanisms: Chiral pions, vector mesons, resonances
  - Neutron charge density

- Pion transverse density from timelike FF
  - Timelike pion FF from $e^+e^-$ data
  - Singular charge density at $b \to 0$
  - Pointlike $q\bar{q}$ configurations in pion

New insights into nucleon’s partonic structure
New way to study $\rho, \omega$ couplings
Nucleon structure: Partonic description

- QCD vacuum not empty
  
  Strong non-perturbative gluon fields of size $\rho \ll 1 \text{ fm}$ \hspace{1cm} ← Lattice simulations, analytic models
  
  Chiral symmetry breaking: $\bar{q}q$ pair condensate, $\pi$ as collective excitation

- Slow–moving nucleon $P \sim \rho^{-1}$
  
  $\langle N|J_\mu|N\rangle$ from Euclidean correlation functns
  
  No concept of particle content
  Cannot separate “constituents” from vacuum fluctuations

- Fast–moving nucleon $P \gg \rho^{-1}$
  
  Closed system: Wave function description
  variable particle number, $x_i$, $k_T$ \hspace{1cm} Gribov, Feynman
  
  Current operators “count” particle nr $\times$ charge
  
  Physical properties:
  Longitudinal momentum densities \hspace{1cm} PDFs
  Transverse distributions \hspace{1cm} → Form factors, GPDs
  Orbital motion \hspace{1cm} TMDs
Nucleon structure: Transverse densities

- Current matrix element parametrized by invariant form factors
  \[ \langle N' | J_\mu | N \rangle \rightarrow F_1(t), F_2(2) \]  
  Dirac, Pauli

- Transverse charge density \( t = -\Delta_T^2 \)
  \[ F_1(t) = \int d^2b \, e^{i\Delta_T b} \rho(b) \]  
  2D Fourier

  Transverse density of charge in fast-moving nucleon \( b \) displacement from transverse C.M.

- Proper density for relativistic system
  \[ \rho(b) = \sum_{\text{charge}} \int dx \, \psi^*(x, b/\bar{x}, ..) \psi(x, b/\bar{x}, ..) \]

  Cumulative effect of constituents at transv. position \( b \)

- More general: Reduction of GPDs
  \[ \rho(b) \leftrightarrow \text{transverse size in hard exclusive processes} \]
Nucleon: Transverse density from spacelike FF

- Nucleon transverse charge density from spacelike form factor data

  Experimental and incompleteness errors estimated Venkat, Arrington, Miller, Zhan 10

- Neutron density positive at distances $b \sim 0.5 - 1 \text{fm}$ Miller 07

  Contradicts naive picture of $n = p(\text{center}) + \pi^-(\text{cloud})$

  Dynamical explanation?

  Nucleon periphery $\leftrightarrow$ exchange mechanisms?

\[
\rho(b) = \int_{0}^{\infty} \frac{d\Delta}{2\pi} \Delta J_0(\Delta b) \ F_1(t = -\Delta^2)
\]
Nucleon: Dispersion representation

- Dispersion representation of form factor

\[ F(t) = \int_{4m_{\pi}^2}^{\infty} \frac{dt'}{t' - t + i0} \frac{\text{Im } F(t')}{\pi} \]

Spectral function \( \text{Im } F(t') \) describes "process" \( \gamma^* \rightarrow \text{hadronic system} \rightarrow N \bar{N} \)

Unphysical region: Spectral function from dispersion analysis, \( \chiPT \) near threshold, pQCD \( t \rightarrow \infty \)

- Transverse density

\[ \rho(b) = \int_{4m_{\pi}^2}^{\infty} \frac{dt}{2\pi^2} K_0(\sqrt{t}b) \text{Im } F(t) \]

\( K_0 \sim e^{-b\sqrt{t}} \) exponential suppression of large \( t \)

Dispersion integral selects \( \sqrt{t} \sim 1/b \):
"Filter" for spectral density \( \text{Strikman, CW 10} \)

New tool to analyze exchange mechanisms!
Nucleon: Spectral analysis of charge density

- Analyze contributions of spectral mass regions to transverse charge density
  Quantitative, model-independent, Miller, Strikman, CW, in preparation.
  Spectral densities from Belushkin, Hammer, Meissner 07

- Isovector density
  Near-threshold $\pi\pi$ relevant only at $b > 2\, \text{fm}$
  Chiral dynamics applicable only at very large distances! SW10

  Intermediate $b = 0.5 - 1\, \text{fm}$ dominated by $\rho$, with $10 - 15\%$ correction from first $\rho'$

- Isoscalar density
  No chiral contribution, $3\pi$ extremely small

  Intermediate $b = 0.5 - 1\, \text{fm}$ from $\omega$, with $20 - 50\%$ contribution from $K\bar{K}$, $\pi\rho$

Neutron charge density at intermediate $b$
unrelated to pion cloud! Explained instead by effective dynamics in vector meson mass region
**Pion: Transverse density from timelike FF**

- **Spacelike FF poorly known at** $|t| > 1 \text{GeV}^2$
  
  Electroproduction on nucleon, model-dependent. JLab Hall C 6/12 GeV

- **Timelike FF from** $e^+e^-$ annihilation
  
  $|F_\pi|^2$ from cross secn, phase from models/theory

  Resonance–based parametrization from fit to data

  Bruch, Khodjamirian, Kuhn 04. CLEO 05 results not included.

- **Transverse density from dispersion integral**
  
  Miller, Strikman, CW 10

  $$\rho_\pi(b) = \int_0^\infty \frac{dt}{2\pi^2} \frac{1}{4m_\pi^2} K_0(\sqrt{tb}) \text{Im} F_\pi(t)$$

  Fully calculable, precise, error estimates

  Singular charge density at center of pion
• Singular charge density at center due to point-like configurations in pion wave functn

Configs of size \( r \ll R_\pi \), mostly elementary \( q\bar{q} \)

Observable in other high-momentum transfer processes: \( \gamma^*\gamma \rightarrow \pi^0, \pi + A \rightarrow 2 \text{ jets}, \ldots \)

Universal property

Large-size configs with \( x \rightarrow 1 \) cannot account for empirical charge density at \( b \rightarrow 0 \)

Miller, Strikman, CW 10

• 2D image of fast-moving pion

First accurate transverse image based on data!
More general: GPDs

- Generalized parton distribution
  - Form factor of partons with longit. momentum $xP$
  - QCD operator definition $\langle N' | \text{twist-2} | N \rangle$, universal
  - Probed in hard exclusive processes in $ep/\gamma p$: $J/\psi$, vector mesons at HERA, DVCS at HERMES, COMPASS, JLab 6/12 GeV

- Transverse spatial distribution of partons
  \[ \text{GPD}(x, t) = \int d^2 b \ e^{ib\Delta T} \ f(x, b) \]
  - Tomographic image of hadron at fixed $x$, changes with $x, Q^2$
  - $\rho(b) = \int dx \ f_{q-\bar{q}}(x, b)$ Reduction of GPD

- Essential input to $pp@LHC$
  - Impact parameter dependence of cross section for hard processes
  - Underlying event, multiparton processes, gap survival in diffraction

$\xrightarrow{\text{MPI@LHC2010 Glasgow}}$
Summary

- Elastic form factors provide important information on partonic structure through transverse charge/current densities

- Dispersion integral for $\rho(b)$ samples spectral function at energies $\sqrt{t} \sim 1/b$, allows for systematic study of the various exchange mechanism

- Nucleon charge densities at intermediate distances $b = 0.5 - 1.5$ fm governed by vector mesons; pion cloud relevant only at $b > 2$ fm

- Singular charge density in pion reveals pointlike $q\bar{q}$ configurations in partonic wave function